Alternative future 6.x nm EUV sources from strong in-band line emission

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1. Introduction to work

- Much research is proceeding into developing a 6.x nm light source for advancing beyond extreme ultraviolet (BEUV) as a feasible future lithography source [1]
- Maximum reflectivity of multi-layer mirrors (MLM) has been shown to be about 50% at 6.656 nm and 43% at 6.63 nm [2]
- Uncertainty exists as to the exact wavelength to be chosen for BEUV, therefore it's important to investigate other possible candidate materials in 6.5 - 6.8 nm region
- In this work phosphorus (P) and molybdenum (Mo) are investigated as possible 6.x nm line emitting sources

2. Experimental set-up & details

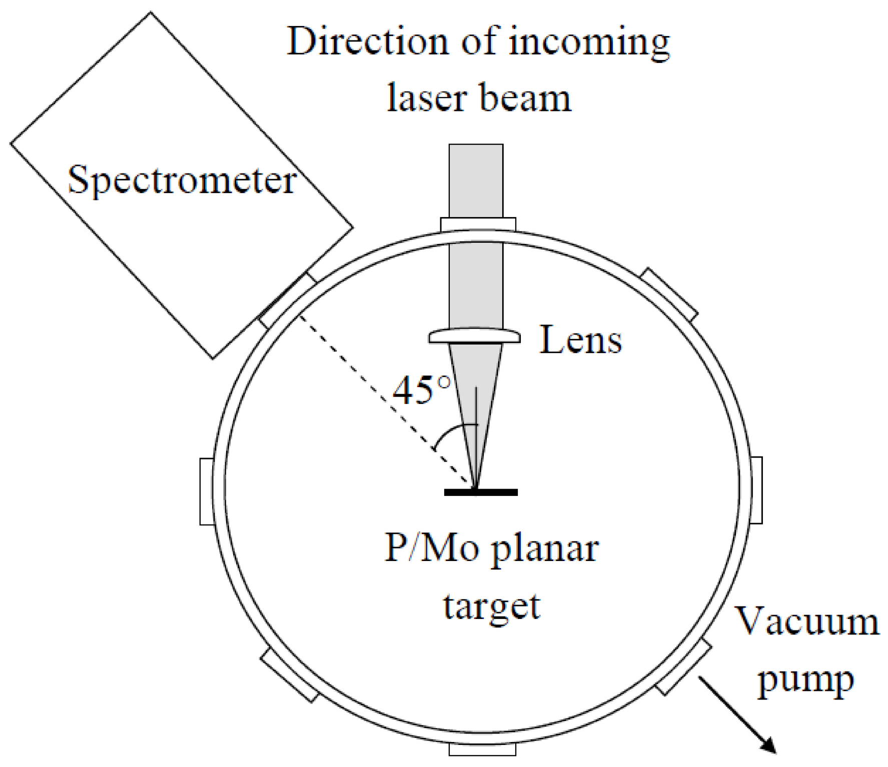

Figure 1: Experimental set-up

- P and Mo plasma produced using 10 ns Nd:YAG laser (λ=1064 nm)
- Flat-field grazing incidence spectrometer used to observe plasma emission at 45° to the target normal
- 100 mm focal length lens was fixed for 50 µm spot size
- Laser energy was varied by changing *Q*-switch delay

3. Emission spectra & theoretical calculations

- Emission spectra of P fitted with theoretical spectra using COWAN code in **Fig 2(a)**. 6.6 nm line emission observed due to $2p^5 - 2p^43d$ and $2p^4 - 2p^33s$ transitions of P^{6+} and P^{7+} ions [3]. Fitted with COWAN plot with ion populations weighted for a temperature of 25 eV

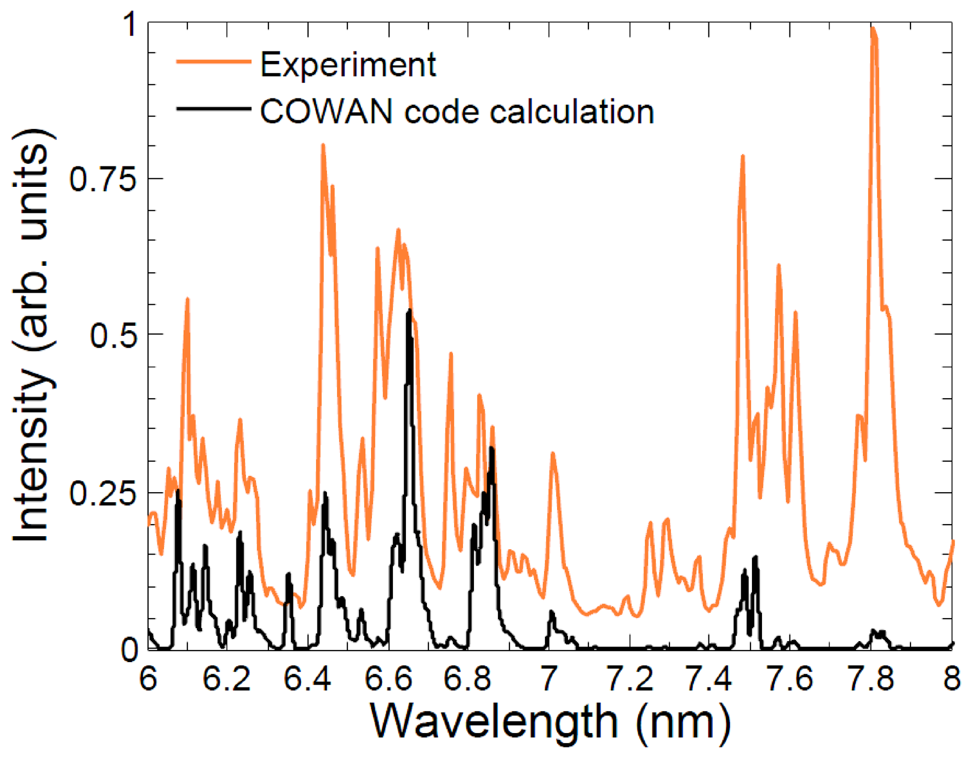

Figure 2(a): Spectrum of P plasma using 10 ns Nd:YAG laser with COWAN code calculations

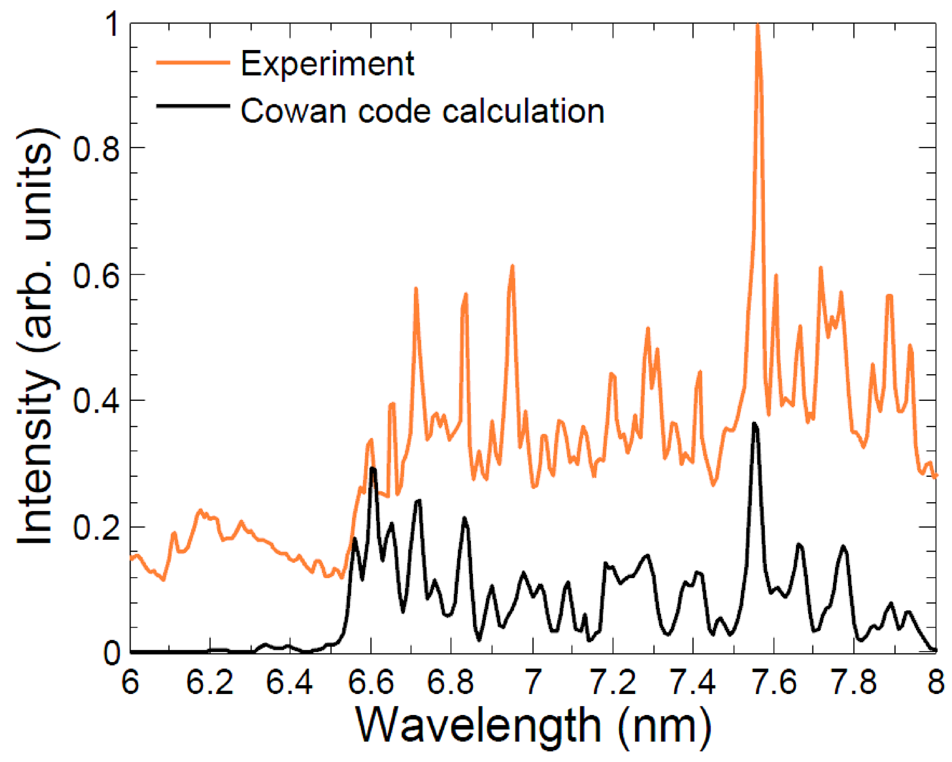

Figure 2(b): Spectrum of Mo plasma using 10 ns Nd:YAG laser with COWAN code calculations

- Spectra of laser produced Mo plasma is also fitted with theoretical spectra using COWAN code in **Fig 2(b)**. Line emission from 6.5-6.8 nm due to $3p^63d^9 - 3p^53d^{10}$, $3p^63d^8 - 3p^53d^9$ and $3p^63d^7 - 3p^53d^8$ transitions of Mo^{15+} to Mo^{17+} ions [4]. Fitted with COWAN plot with ion populations weighted for a temperature of 65 eV

4. Plasma temperature

- FLYCHK code used to calculate the charge state distributions of P **Fig 3(a)**, and Mo **Fig 3(b)** plasma in non-local thermodynamic equilibrium (non-LTE). Both calculations were carried out using an electron density of 10^{21} cm^{-3}

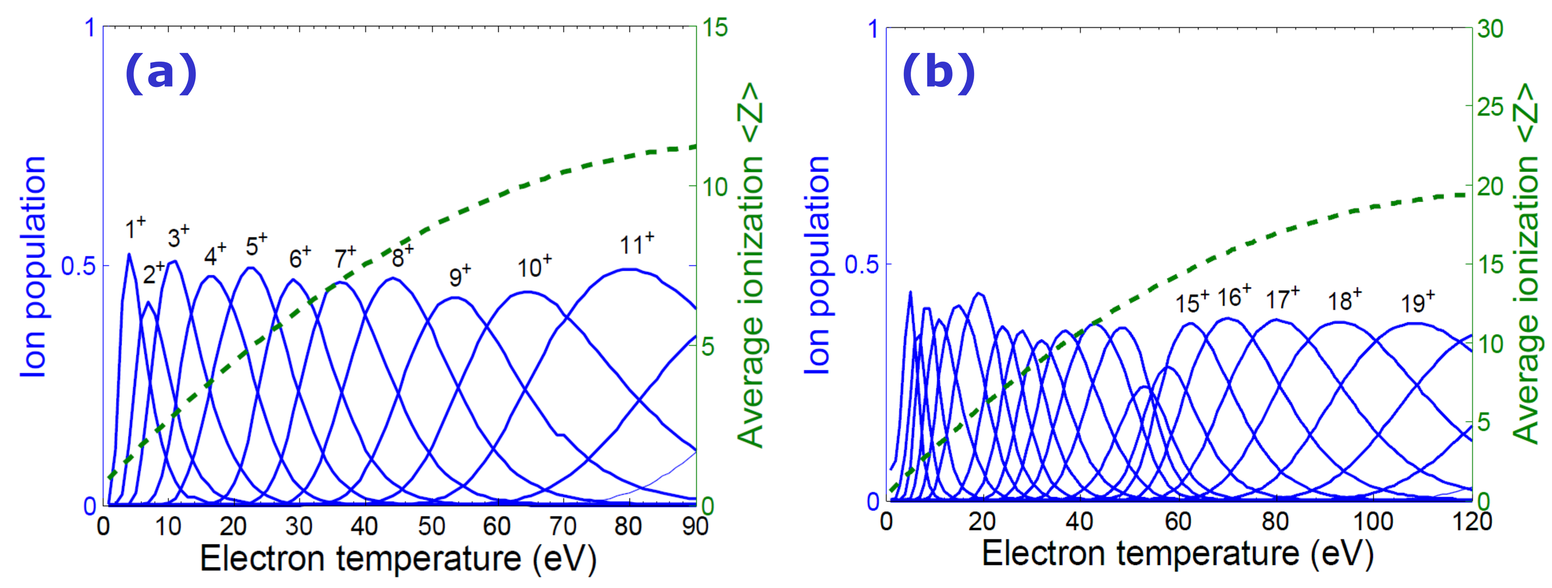

Figure 3(a, b): Ionic populations and average ionization of P (a) and Mo (b) as a function of electron temperature

- Calculated electron temperatures of 30 eV and 60-80 eV for optimized P and Mo 6.x nm emission respectively. Previous modeling of Gd and Tb [5, 6] predict electron temperature requirements of 110-140 eV for Gd and 150 eV for Tb. Therefore optimal in-band emission is achievable at much lower temperatures, and for P this is of the same order as required for Sn at 13.5 nm

5. Phosphorus line emission vs. Gd/Tb UTA

- **Fig 4(a)** shows the position of the 0.6% band centered on 6.656 nm for La/B_4C structure MLM plotted with P and Gd [7] experimental emission spectra. **Fig 4(b)** shows the location of the 0.6% band centered on 6.63 nm for La_2O_3/B_4C structure MLM plotted with P and Tb [8] experimental emission spectra. Both figures show peak emission of P matches well with in-band of both MLM, whereas both Gd and Tb peaks are not matched as. However, spectra do not represent actual line intensities but are only shown on similar scales for the purpose of comparing their wavelengths of emission.

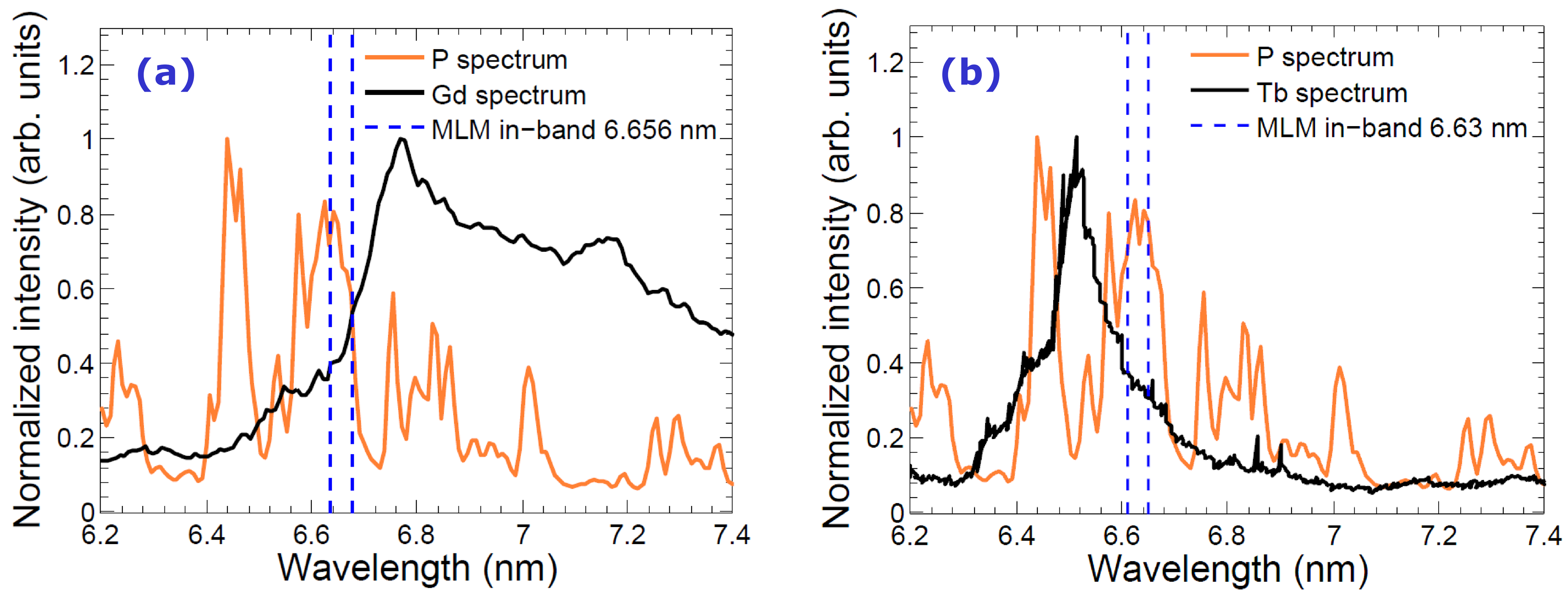

Figure 4(a, b): In-band location of current 6.646 nm (a) and 6.63 nm (b) MLMs shown with spectra of P line emission and Gd (a) and Tb (b) UTAs

6. In-band emission

- Effect of laser intensity on conversion efficiency (CE) of P plasma is calculated for 6.63 nm and 6.656 nm MLMs, using experimental spectra of P. CE increases initially and then plateaus at around 7×10^{11} W/cm^2. Optimum emission can be achieved at lower intensity than Gd or Tb. $T(eV) \propto A^{1/5}[\lambda^2\varphi(W/cm^2)]^{3/5}$ [9]

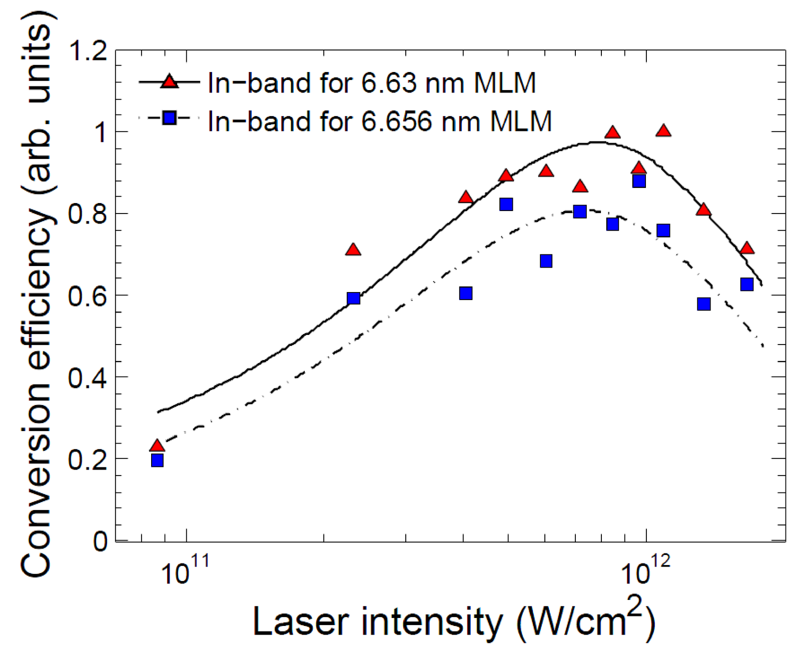

Figure 5: Normalized CE of P as a function of laser intensity

References

[1] G. O'Sullivan, D. Kilbane and R. D'Arcy, J. Mod. Optic. **59**, 855 (2012)
[2] Y. Platonov *et al*, Proceedings of the 2011 International Workshop on EUVL (EUV Litho Inc., Maui, Hawaii, 2011)
[3] B. C. Fawcett *et al*, J. Phys. B **3**, 564-71 (1970)
[4] T. Shirai *et al*, J. Phys. Chem. Ref. Data, Monograph No. 8, AIP Press, Melville, NY, 632 pp. (2000)
[5] D. Kilbane and G. O'Sullivan, J. Appl. Phys. **108**, 104905 (2010)
[6] B. Li *et al*, Appl. Phys. Lett. **99**, 231502 (2011)
[7] C. O'Gorman *et al*, Appl. Phys. Lett. **100**, 141108 (2012)
[8] S. S. Churilov *et al*, Phys. Scr. **80**, 045303 (2009)
[9] D. Colombant and G. F. Tonon, J. Appl. Phys. **44**, 3524 (1973)

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